Coupling for ESM: The integrated Earth System Model (iESM)

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Three major objectives of iESM project

• Create a first generation integrated Earth System Model (iESM) with both the human components of an IAM and a physical ESM

• Develop linkages within the iESM and apply the model to improve our knowledge of coupled physical, ecological, and human system

• Add hydrology and water demand, allocation, and availability to IA.
Multi-phase coupling of IAMs and ESMs / EMICs
Feedback coupling of IAMs and ESMs / EMICs?

CMIP5

IAM → RCP Handshake → ESMs / EMICs

C stocks, productivity

Climate

Up/down scaling (space and time)

Atm CO₂

CMIP6 ?

Accelerated Climate Modeling for Energy
The integrated Earth System Model (iESM)

Human system
(GCAM3)

Earth system
(CESM1.1)

Policy

Economy

Energy

Water

Land

Atmosphere

Ocean / Ice

Climate

Land / Ice

Emissions

Land Use/ Land Cover

Climate, Productivity, etc.
iESM links 4 models: GCAM, GLM, CLM, & CESM

1. GCAM
   (Human Dimensions Elements only; 15 ghgs, aerosols, SLS; 14 geopolitical regions; 151 Ecoregions)

2. GLM
   (½ x ½ degree grid land-use-land-cover.)

3. CLM & 4. CESM

ESM1

Fossil Fuel & Industrial Emissions (Gridded)
Two major experiments

- **Experiment 0**: One-way coupling
- **Scientific Question**: *How much difference does land-use emissions mitigation policy make for near-term and long-term climate change?*
Three major experiments: Two complete

- **Experiment 0**: One-way coupling
  - **Scientific Question**: How much difference does land-use emissions mitigation policy make for near-term and long-term climate change?

- **Experiment 1**: Two-way coupling of the land-use components
  - **Scientific Question**: How much difference does climate change make for crop yields and land use?
iESM Experiment 1: Introduce two-way coupling between climate systems and human systems

CO₂ and climate change impacts on GCAM crop yields and carbon stocks
Design and Model Coupling in the iESM: Expt. 1

**GCAM 3.0**
- 15 ghgs, aerosols, SLS; 14 geopolitical regions; 151 Ecoregions

**GLM**
- $\frac{1}{2} \times \frac{1}{2}$ degree grid
- land-use-land-cover

**CESM1**
- Including CLM4
  - $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$
  - Land cover, wood harvest

Begin the process of 2-way coupling through **ecosystem productivity changes** from CO$_2$ and climate.
Experiment 1: Feedback changes land allocation

Thornton et al., 2016, in review
Experiment 1: Feedback alters commodity prices and fossil fuel emissions

Thornton et al., 2016, in review
Experiment 1: Feedback alters global carbon cycle

Thornton et al, 2016, in review
How robust is this signal across other models and approaches?

• Motivation:
  – We use a single climate and crop model, collapsing an important uncertainty.

• Approach:
  – Stand alone GCAM experiments using productivity change from CMIP5 and AgMIP

• Preliminary Findings:
  – We tend to have lower productivity growth than other climate models, but higher than other crop models.
iESM Experiment 1: Introduce two-way coupling between climate systems and human systems

1. CO₂ and climate change impacts on GCAM crop yields and carbon stocks
2. Land use and land cover change
3. Expt 1 feedback
4. Ocean system
5. Climate (T, P, q, rad)
6. Land system

Fossil Fuel Emissions
Atm CO₂
Human systems
Land use and land cover change
Expt 1 feedback
CO₂ and climate change impacts on GCAM crop yields and carbon stocks
iESM Experiment 1: Introduce two-way coupling between climate systems and human systems

1. CO₂ and climate change impacts on GCAM crop yields and carbon stocks
2. Land use and land cover change
3. Atm CO₂ feedback to land system
4. Ocean system feedback to climate system
5. Climate system feedback to human systems
6. Human systems feedback to climate system

Fossil Fuel Emissions

Atm CO₂

Climate (T, P, q, rad)

Human systems

Land system

Expt 1 feedback
Design and Model Coupling in the iESM: Expt. 1

Freeze the Emissions Pathways

GCAM 3.0
15 ghgs, aerosols, SLS; 14 geopolitical regions; 151 Ecoregions

GLM
½ x ½ degree grid land-use-land-cover

CESM1
Including CLM4

½°x½° Land cover, wood harvest

Begin the process of 2-way coupling through ecosystem productivity changes from CO₂ and climate
Design and Model Coupling in the iESM: Expt. 1

Begin the process of 2-way coupling through ecosystem productivity changes from CO₂ and climate

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CESM1
Including CLM4

Freeze the Emissions Pathways

½°x½° Land cover, wood harvest
Issues in Translating LULCC from GCAM->CESM

The Problem

Forest

Pasture

Di Vittorio et al, 2015

The Solution

Forest

Pasture

ACME Accelerated Climate Modeling for Energy
Impacts of Translating LULCC from GCAM->CESM

- **a)** iESM Total Vegetation Carbon (TOTVEGC)
- **b)** iESM difference in TOTVEGC
- **c)** iESM atmospheric CO$_2$ (CO2)
- **d)** iESM difference in CO2

Figure 10. Comparison between iESM simulations of
(a–b) vegetation carbon and  
(c–d) atmospheric CO$_2$ concentration. Differences are
NEWLUT minus OLDLUT. Due to additional forest area, the NEWLUT simulation significantly increases vegetation carbon gain and

decreases atmospheric CO$_2$ gain over the OLDLUT simulation.

For CESM because there is no other information to constrain
forest area, and may be applicable only to the RCP4.5 sce-
nario. Although this limits NEWLUT to including only two-
thirds of the total afforestation, adding more forest area to
CESM would be arbitrary without additional land cover in-
formation. Nonetheless, the increased afforestation in NEW-
LUT results in an increase in net land carbon uptake over the
OLDLUT case due to a sustained increase in average annual
land carbon uptake after 2020 (Fig. 9). As a result, the NEW-
LUT simulation increases vegetation carbon gain by 19 PgC
and decreases atmospheric CO$_2$ gain by 7.7 ppmv from 2005
to 2040 in comparison to OLDLUT (Fig. 10). The NEWLUT
simulation also decreases soil carbon gain by about 1.5 PgC
over this period (data not shown).

Simple linear extrapolation of the iESM vegetation carbon
gain and atmospheric CO$_2$ gain from 2005 to 2100 increases
these changes to approximately 52 PgC and 21 ppmv, and ex-
tending CESM forest area to match GCAM total afforesta-
tion could potentially increase these changes to 88 PgC and
36 ppmv in 2100. These are rough estimates that use 2005 as
a starting point to reduce the high slope associated with the
initial increase from 2015 to 2020, and also assume that ad-
dditional forest area continues to gain carbon for 60–80 years
after it is established. Regardless of the absolute accuracy
of these extrapolations, the potential gain in vegetation car-
bon alone for CESM with full afforestation is on the order of
estimates of net cumulative land use change emissions dur-
during 1850–2000, which range from 110 to 210 PgC (Table 3
in Smith and Rothwell, 2013). For comparison, the range of
CMIP5 vegetation carbon stock gains for RCP4.5 is about
50 to 300 PgC from 2005 to 2100, with most gains being
less than 150 PgC and relatively linear (Fig. 2 in C. Jones et
al., 2013). An increase in gain of 88 PgC would dramatically
shift CESM vegetation carbon dynamics in relation to the
other ESMs. The corresponding 36 ppmv decrease in atmo-
spheric CO$_2$ is nearly one-third of the difference between the
prescribed 2100 concentrations of the RCP4.5 (⇠540 ppmv)
and RCP2.6 (⇠420 ppmv) scenarios (Fig. 1 in C. Jones et
al., 2013). More importantly for CESM's ability to robustly
simulate the effects of the RCP scenarios on the earth sys-

tem, the prognostic CESM atmospheric CO$_2$ concentration
in 2100 for RCP4.5 is 610 ppmv (Keppel-Aleks et al., 2013),
and a decrease from 610 to 574 ppmv has an approximate
decrease in radiative forcing of 0.33 W m$^{-2}$, which is non-
trivial with respect to the 4.5 W m$^{-2}$ target. While these car-
bon cycle changes in the CESM component of iESM may
have a significant effect on climate, it is important to note
that the carbon cycle effects of afforestation in CESM are
not identical to those in GCAM or GLM because these three
models have different biogeochemistry and vegetation mod-
els. These differences in carbon cycles, however, do not ob-
viate the need for making both land cover and land use con-
sistent between IAMs and ESMs in order to best match the
prescribed radiative forcing scenario.

Different implementations of land cover and land use
among IAMs and ESMs also reduce the fidelity between
RCP scenarios and their associated effects on the earth sys-
tem. Figure 8 shows that most of the additional forest area in
NEWLUT occurs on grassland and shrubland, and that these
lands generally coincide with areas of limited potential for-
est. The OLDLUT could not add forest area where no poten-
tial forest area exists, and the rate of forest carbon accumu-
lates over this period (data not shown).
**iESM Experiment 1:**
Introduce two-way coupling between climate systems and human systems

1. CO₂ and climate change impacts on GCAM crop yields and carbon stocks
2. Land use and land cover change
3. Expt 1 feedback
4. Ocean system
5. Climate system (T, P, q, rad)
6. Land system

Fossil Fuel Emissions → (fixed) Atm CO₂
Design and Model Coupling in the iESM: Expt. 1

Freeze the Emissions Pathways

**GCAM 3.0**
15 ghgs, aerosols, SLS; 14 geopolitical regions; 151 Ecoregions

**GLM**
½ x ½ degree grid land-use-land-cover

**CESM1**
Including CLM4

Begin the process of 2-way coupling through **ecosystem productivity changes** from CO₂ and climate.
Translating Carbon Drivers from CESM->GCAM

Need a proxy to convert CESM Drivers -> GCAM Biomass w/o effects of LULCC

Above-ground C
Below-ground C

CO₂ Fertilization
N Deposition

LULCC

ACME
Accelerated Climate Modeling for Energy
Translating Carbon Drivers from CESM->GCAM

**Carbon Drivers**
- CO₂ Fertilization
- N Deposition
- LULCC

**Change from 1850 baseline**
- Best Proxy: Net Primary Productivity

**Proof of Principle**
- Test Proxies
  - Crops
  - Grass
  - Shrubs
  - Trees

**Net Primary Productivity**

Bond-Lamberty et al, 2014

Translating Carbon Drivers from CESM->GCAM

ACME
Accelerated Climate Modeling for Energy

U.S. DEPARTMENT OF ENERGY
Design and Model Coupling in the iESM: Expt. 2

Fossil-Fuel Emissions

GCAM 3.0
15 ghgs, aerosols, SLS; 14 geopolitical regions; 151 Ecoregions

GLM
½ x ½ degree grid land-use-land-cover

CESM1
Including CLM4

⅓°x⅓° Land cover, wood harvest

2-way coupling through ecosystem productivity changes from CO₂ and climate
iESM Experiment 2:
Additional two-way coupling by passing modified fossil fuel emissions to atmosphere

- Fossil Fuel Emissions
- Atm CO$_2$
- Ocean system
- Climate (T, P, q, rad)
- Human systems
- Land system
- Land use and land cover change

CO$_2$ and climate change impacts on GCAM crop yields and carbon stocks
Expt 2 additional feedback
Irrigation in Central Valley has large influence on surface evapotranspiration with statistically significant remote effects on North American monsoon rainfall (Lo et al. 2013 GRL)
Water: Preliminary Results

- Enhance representation of irrigation in ALM
  - Irrigation amount is calibrated against FAO census data
  - Both surface and groundwater irrigation source constrained by FAO census data
  - Different irrigation methods adopted

Sprinkler irrigation: water is applied uniformly as precipitation

Flood irrigation: water is applied to the root zone in 30 minutes

Drip irrigation: Water required is immediately transpired rather than added to the soil column
Water: Preliminary Results

• Numerical experiments with offline ALM

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<tr>
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• Irrigation increases ET and reduces runoff and groundwater storage
• Irrigation effects on ET are largely dependent on the irrigation methods
Next: Coupling Climate to Water Cycle

The GCAM Systems

Water Demand
- Electricity Gen. Sector Demands
- Primary Energy Sector Demands
- Manufacturing Sector Demands
- Domestic Sector Demands
- Agricultural Sector Demands
- Livestock Sector Demands

Water Supply
- Global Water Availability Model

Economy System
- Regional Resource Bases
- Energy Markets
- Energy Demand Technologies
- Energy Supply
- Regional Energy Conversion Technologies
- Regional GDP
- Energy Demand
- Energy Production, Transformation and Use

Energy System
- GHG Emissions
- Regional Labor Force
- Regional Labor Productivity

Climate System
- Ocean Carbon Cycle
- Terrestrial Carbon Cycle
- Atmospheric Composition, Radiative Forcing, & Climate

Water System
- H₂O for Hydropower
- H₂O for Irrigation

Hejazi et al, 2014
Opportunities from further integration

- **Immediate** tests of climate impacts for future scenarios.
- Tool to enable “no regrets” scenario/path development.
- Advances in internally consistent treatment of water, energy, and climate in mitigation pathways.
- Quantification of impacts of feedbacks and interactions that are yet to be treated under current protocols and yet could be significant on mitigation timescales.